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STUDIES FOR STUDENTS.

THE MAPPING OF THE CRYSTALLINE SCHISTS.[1]

II. BASAL ASSUMPTIONS.

Introduction.

- Deformation under compressive stresses either by flow or by rupture.
- Deformation zones of the lithosphere.
- Mechanics of deformation by flow.
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- Direct genetic relations of joint systems to systems of normal faults.
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- Nature of evidence for establishing a fault.
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INTRODUCTION.

In an earlier paper bearing this general title[2] the writer has discussed the methods of mapping the crystalline schists, and taken occasion to emphasize the necessity for a larger use of outcrop maps for all complexly deformed areas. It was also advocated that many peculiarities of rock exposures besides those ordinarily observed be examined and recorded, and their significance be sought in the final interpretation—the drawing of boundaries and the coloring of the map. In the present paper it is proposed to go somewhat deeper into the subject, and to discuss the basal and perhaps unconscious assumptions of the geologist in the making of his map.

If the writer's contention is upheld, it will be shown that methods of mapping have not kept pace with the advance of the science of geology, and that, whereas the mechanics of crustal deformation, as now understood, and observation alike, take account of two distinct methods of rock deformation, geological mappers seem generally to have regarded but one as possessing much significance. The subject is an intricate one and one which does not readily lend itself to absolute demonstration, but in another place concrete examples will be chosen and described in some detail to show that the subject is a much larger one than is ordinarily understood.

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[1] Published with the permission of the director of the United States Geological Survey.

[2] JOUR. GEOL., Vol. X, 1902, pp. 780–92.

DEFORMATION UNDER COMPRESSIVE STRESSES EITHER BY FLOW OR BY RUPTURE.

The stresses within the earth's crust which bring about sufficiently important deformation to affect the tectonic structure of an area may be assumed to be vertical compression due to the weight of superincumbent material, and lateral compression due to crustal shortening from whatever cause,[1] but in the last analysis a result of gravitation. Tensile stresses are locally produced when rocks assume new attitudes under compressive stress, but their importance as a direct cause of deformation over considerable areas is probably subordinate and largely limited to the effect of temperature change in surface masses of igneous rock, and hence may largely be dismissed from consideration in the present discussion.

The generally accepted classification of displacements resulting from earth stresses has been thus expressed by Suess:[2]

> The visible displacements[3] in the earth's superstructure of rock are the result of movements which proceed from the diminution of volume of our

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[1] VAN HISE, "Estimates and Causes of Crustal Shortening," JOUR. GEOL., Vol. VI (1898), pp. 10–64, also, "Earth Movements," *Trans. Wis. Acad. Sci., etc.*, Vol. XI (1898), pp. 465–516.

[2] SUESS, *Das Antlitz der Erde*, 1885, Vol. I, p. 143. See also, MARGÉRIE ET HEIM, *Les dislocations de l'écorce terrestre*, Zürich, 1888, p. 8.

[3] The double meaning of the German and French words *Dislocation* and *dislocation* is especially unfortunate. In continental usage "dislocation" is employed in its more general sense for "displacement" (as for example, in the title of Margérie and Heim's work), and quite generally also in a special sense for "disjointing," or equivalent to "faulting." American usage is, I believe, wholly restricted to the word applied in the latter sense.

planet. Strains brought about by this process indicate an inclination to differentiate themselves into tangential and radial strains, thereby inducing horizontal (that is, compressive and folding), and vertical (that is, depressional) movements. Displacements have therefore been separated into two principal groups, by one of which have been produced more or less horizontal, by the other more or less vertical changes of position of portions of the crust.

Under compressive stresses rocks may suffer deformation in one or both of two ways: by flow, when under sufficient load; and by rupture, when the load is insufficient to cause flow.

DEFORMATION ZONES OF THE LITHOSPHERE.

It has been shown that at a depth of 10,000 meters, more or less, even the strongest rocks must find relief from stress by flow, and hence below that depth there must be a zone which, as respects its manner of deformation, may be called the zone of flow.[1] At very moderate depths relief from stress will be obtained by rupture, and this uppermost belt is therefore denominated the zone of fracture. Since, however, the depth at which rocks will flow is dependent primarily upon their crushing strength, there will be an intermediate zone or belt within which deformation will take place partly by rupture and partly by flow (zone of combined fracture and flow). There are many other conditions—such as amount of contained water, elevation of isogeotherms, etc.—which modify the depths of the zone of flow, but they need not be taken up here.

It is clear from these considerations that rocks may be deformed at one period by fracture (when under light loads), and at another time by flow (when below a depth of 10,000 meters, more or less). During a general elevation of a region deformation by flow within a given rock mass, will in general precede that by fracture, and the structures which arise from fracture will be superimposed upon those developed by flow. During a considerable subsidence of a province structures due to flow will be superimposed upon fracture structures and either wholly or partially efface them. The presence in the same rocks of well-developed flow structures and well-marked fracture structures independent as regards their direction of the flow structures, is strong evidence that the deformation by fracture was subsequent to that by flow. Moreover, in the very nature of the problem it is to be assumed that a fracture structure will in most cases be superimposed upon a flow structure, owing to the fact that degradational forces, as they continuously remove the upper layers of the lithosphere, gradually relieve the load upon the deeply buried rocks, until these are at last exposed to our view. This, however, is not the only reason why we should assume a fracture structure to be the later when found in conjunction with a flow structure, for fracture structures are quickly effaced by flow, whereas flow structures, though disturbed and distorted, are not obliterated by fracture structures.

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[1] VAN HISE, "Principles of North American Pre-Cambrian Geology," *Sixteenth Ann. Rept U. S. Geol. Survey,* Part I (1896), pp. 589–94.

THE MECHANICS OF DEFORMATION BY FLOW.

The mechanics of this problem is a large subject fully treated elsewhere[1] and may well be largely omitted from this discussion. Deformation by flow produces flexuring or folding of the initially horizontally bedded rocks. The position and the shape of the individual flexures will be determined by many factors: as, the position of old shore lines with their planes of weakness, and the initial dip of the beds resting upon them; the position of masses of igneous material (which by refusing to yield as readily as the bedded rock may elevate a portion of the latter above the zone of flow and cause rupture by thrust at the planes of maximum mashing); the position of earlier planes of rupture or foliation, etc. Flexuring is thus the method by which the heavily loaded rocks accommodate themselves to lateral compression, and results in a crustal shortening and thickening. In every fold there is a local compression normal to the beds in the limbs of the fold, and a local tension in the same relative direction in the arches, the tendency of which is to cause a local transfer of rock material from the limbs to the arches, the limbs becoming thinner and the arches thicker by this process. Foliation planes, or planes of easy separation, are also produced, which in moderately compressed folds make small angles with the axial plane of the folds,[1] but in closely compressed folds they are approximately parallel to that plane.

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[1] WILLIS, "Mechanics of Appalachian Structure," *Thirteenth Annual Report U. S. Geol. Survey*, Part II, 1891–2, pp. 211–282. VAN HISE, *loc. cit.*, pp. 589–668; see also SUESS, *Antlitz der Erde*, Vol. I, pp. 142–189; MARGÉRIE ET HEIM, *loc. cit.*, 49–87.

MECHANICS OF DEFORMATION BY RUPTURE.

The problem of deformation by lateral compression of a crustal block has been treated from a mathematical standpoint by Becker,[2] his discussion assuming the section of crust to be an elastic solid.

This block may be regarded, then, as subjected to stresses from which it acquires the properties of an anisotropic medium in which the greatest and the least axes of the strain ellipsoid lie in the horizontal plane, owing to the fact that gravity opposes an elongation of the particles in the vertical direction. The effect of such stress is to produce a system of vertical planes of dislocation which in a mass of infinite resistance (perfect elasticity) would make 45° with the direction of pressure, but otherwise (if more or less plastic) the angle would be less. With pressures rapidly applied it is believed that rocks behave like highly elastic bodies. The best evidences that such is the case seem to be furnished by the almost universal observation that the most prominent joint planes are nearly vertical (except in subsequently tilted rocks) and so generally nearly perpendicular to one another;[3] and by the experiments of Crosby,[4] who found that a system strained to a point far below that of rupture (near which plasticity becomes for the first time an important factor) is relieved from its stress by dislocation through shock communicated to the system (for example, by an earthquake). In the opinion of the writer, these considerations render invalid many of the data collected from test pieces in laboratories. Elsewhere the writer has developed this subject more extensively.[1] It has there been pointed out that the production of a system of vertical and perpendicular joint planes may be, and probably would be, but the first step in the process of relieving by rupture the stresses within a crustal block. Bv the formation of prismatic joints the potential energy of the system is lowered and a readjustment of the stresses brought about. Furthermore, a tendency is set up favoring local depression, for the reason that rocks in the zone of fracture support their load by their rigidity, and this element of rigidity has been much reduced through the system of dislocations. The crustal block rests upon the rocks in the zone of flow, which are in a condition of potential fluidity, or potential viscosity. The differences of composition and density within the zone of flow, combined with the varying perfection of the joint planes within the zone of fracture (which may be due to lack of homogeneity and perhaps to other causes), furnish conditions for a most irregular and unequal depression of the component blocks produced by the dislocation. On the basis of experiments and observation alike it is believed that the type of tectonic structure produced, before planed down by erosive agencies, may be well illustrated by that of a mosaic, the backing of which has been removed and the component blocks so disturbed as to stand at different altitudes, but with similar axes parallel.

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[1] See this JOURNAL, Vol. X, p. 787.

[2] GEO. F. BECKER, "Finite Homogeneous Strain, Flow, and Rupture of Rocks," *Bull. Geol. Soc. Am.*, Vol. IV (1893), p. 50; see also VAN HISE, *loc. cit.*, p. 672.

[3] A. DAUBRÉE, *Études synthetiques de géologie expérimentale*, Part I (Paris, 1879), pp. 300, 301; see also BECKER, *loc. cit.*, p. 73.

[4] W. O. CROSBY, "The Origin of Parallel and Intersecting Joints," *Am. Geol.*, Vol. XII (1893), pp. 368–75.

A resumption, or, what is more likely, a continuation, of strong compression of an area in the same horizontal plane, or a second shock communicated to it, would doubtless produce a result of a somewhat different character from the first. The resultant of the lateral compressive stress is by reason of the ready-formed joint-planes resolved in directions parallel and perpendicular to them, the former producing a shear along the planes themselves, and the latter a shear along the diagonals of the blocks of the primary system. Torsional stresses are also set up so as to produce fracturing at the edges of the prismatic blocks. If the direction of the new compression made a large angle with the direction of the first, the directions of the new planes of dislocation would be difficult to determine, and torsion would be at a maximum. If, however, its direction corresponded closely to the first, as is most likely if it occurred in the same general period of disturbances affecting the area, the later planes of dislocation would in their directions bear a simple relation to the earlier. New depression of the area would quite likely follow the new dislocation.

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[1] *Twenty-first Annual Report U. S. Geol. Survey*, Part III, pp. 124–33.

Gilbert has shown that within an area which is undergoing depression along fault planes it is likely that earthquakes will follow one another in succession, owing to the fact that orographic blocks are supported in part by the friction along their vertical walls, and that starting friction is greater than sliding friction.[1] The momentum acquired by the slipping block is effective in reducing temporarily the energy of the system, and time is required for its recovery.

To summarize the mechanics of crustal deformation by rupture, it may be assumed that its result would probably be to produce vertical polygonal prismatic blocks bounded by joint and fault planes in a number (large or small) of parallel series intersecting one another, and that these blocks would stand at relatively different altitudes.

SYSTEMS OF FAULTS.

Continental European geologists have quite generally recognized the importance of systems of normal faults in bringing about important deformations, and have described such systems in many widely separated areas. This may, in fact, be said to constitute the most marked line of cleavage between the structural geological investigations of Europe and of America. The trend of European investigation in this regard was early given by Leopold v. Buch in Germany and Élie de Beaumont in France. The latter correctly located along the Rhine valley[2] parallel lines of faults, and, following the theory of the time, supposed the mountain masses upon either side of the Rhine valley to have been forced up above their former level so as to produce a deep channel. That there are many parallel faults which follow the direction of the valley walls of the Rhine has been abundantly proven by later investigations.[1] Today the presence of numerous dislocations in parallel and often intersecting series[2] has been recognized in many European areas extending from the steppes of southern Russia upon the east, to the Pyrenees upon the west, to describe which there have been brought into use a considerable number of special terms. Some of these terms have no equivalent English expresssion, and such as have are, in some cases, unnecessarily long. Among the foreign terms are: Ger. *Bruchfeld*, Fr. *champs des fractures* (area of dislocations); Ger. *Bruchnetz*, Fr. *réseaux régulier des failles* (fault net-work); Ger. *Senkungsfeld* (sunken area); Ger. *Horst*, Fr. *horst* or *mole* (elevated area left between two or more sunken areas); Ger. *Scholle* (orographic block); Ger. *Graben* (long and narrow sunken block); Ger. *Brücke* (long and narrow elevated block); Ger. *Thurm* (relatively high block of nearly equal basal dimensions); Ger. *Kessel* (relatively low block of nearly equal basal dimensions); etc.

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[1] GILBERT, "A Theory of the Earthquakes of the Great Basin, with a Practical Illustration," *Am. Journ. Sci.* (3), Vol. XXVII, 1884, pp. 49-53.

[2] DUFRENOY ET ÉLIE DE BEAUMONT, *Explication de la carte géologique de la France*, Vol. I, p. 398.

It has been especially the work of Suess to correlate the many scattered observations and in the first volume of his monumental work upon *Face of the Earth*[3] to show how the lineaments of the continent are lines of normal faulting, between which great crustal blocks have been depressed by different amounts. In America the description of what I have called the mosaic type of infaulted structure seems to have been restricted to papers upon the Great Basin of the West and upon areas of Newark rocks along the Atlantic border, in both of which provinces only the simplest types of folding are observable. It is highly probable that joints and "minor faults" have been elsewhere frequently observed but thought to have throws so small as to be negligible, the cumulative effects of the small displacements along numerous near-lying planes being overlooked. Faults have too frequently been regarded as isolated phenomena. Within the crystalline areas isolated normal faults have sometimes been supposed to stand in some relation to folds, and because evidence of individual faults is within such areas most difficult to secure, faults have been the last resort of mappers in securing harmony between areal relations and basal hypotheses. The tendency to use faults "to get out of tight places" has probably been in direct ratio to the inadequacy of the hypotheses assumed, and it is, therefore, not strange that faults have been and still are in much disfavor among the most competent and conscientious of American geologists. There are, however, as the writer believes, methods of showing the connection of a *system of faults* with the deformation of an area, through the peculiarities of its joint system, topography, hydrography, outcrop distribution, etc.

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[1] DAUBRÉE, *Description géologique et minéralogique du departement du bas-rhin* (Strasbourg, 1852), pp. 384–406; BENECKE and COHEN, *Geognostische Beschreibung der Umgegend von Heidelberg* (Strasbourg, 1881), pp. 595 ff.; AUSFELD *Geologische Skizze der Gegend von Rheinfelden, Mitth. d. Aárg. naturf. Gesell.*, Vol. III (1882), pp. 83–102; etc.

[2] In German usage the term *System* is generally employed to cover any grouping whether of parallel or of intersecting faults. The author has described under the term "*series of faults*" a group of parallel faults, restricting the use of the larger term "*system of faults*" to the network composed of parallel series. *Twenty-first Ann. Report U. S. Geol. Survey*, Part III, pp. 98 ff.

[3] *Antlitz der Erde*, Prag and Leipzig, 1885.

It will be the object of this paper to point out especially the methods of recognizing fault systems when in conjunction with systems of folds, because in the manner of deformation of an area is involved the most fundamental assumptions of geological mapping. The view that important deformation may be brought about within a folded area of the crystalline schists by a system of normal faults, has hardly been discussed by American geologists, the system of folds being invariably present and supposed to be the only important manner of deformation exhibited.

The impression should not be gained that in the mind of the writer the relative importance of the two methods of deformation is correctly set forth by the space here devoted to each. Deformation by folding is comparatively well understood and exploited in the literature,[1] whereas, as pointed out, the consideration of deformations by a system of fractures is, at least for American areas of the crystalline schists, a new departure in geological mapping.

DIRECT GENETIC RELATIONS OF JOINT SYSTEMS TO SYSTEMS OF NORMAL FAULTS.

As early as 1879 Daubrée brought out clearly the relation of normal faults to planes of jointing. As in the case of so many other important discoveries, however, little weight seems to have been attached to the results by contemporary geologists, and it is doubtful if one geologist in ten now records with care the direction of joint planes. His conclusions the eminent French geologist states as follows :

> 1. The constancy over large areas of the orientation of certain systems of joints has been already confirmed by Sedgwick, de la Beche, John Phillips, and later by other geologists. Further, it has been recognized in Cornwall that the joints maintain their direction in passing from the granite into the schist or *killas* to traverse which they penetrate.
>
> . . . . . This permanence of orientation of the joints . . . . . makes them approach faults, of whose mechanical origin there is no doubt.
>
> It is further known that in many countries joints may be seen passing by various intermediaries into faults properly so called.
>
> 2. The direction of joints in Yorkshire has been the subject of a great number of observations of another eminent geologist, John Phillips,[2] who has collected them into a rose of directions : it results that two directions predominate greatly over the others and that the two directions are perpendicular to each other.
>
> 3. [Referring to the deformation and distortion of fossils in the vicinity of joints.] . . . . . It is therefore an important result to have arrived at a consideration of joints as the effect of rupture the same as faults, which differ above all by their dimensions.
>
> 4. [Referring to the pebbles of conglomerate which have been observed to be neatly cut through by joint planes.] . . . . . A powerful cutting or shearing action has operated in the formation of joints.
>
> To summarize, the characteristic feature which manifests itself in the innumerable fissures of the earth's crust is a parallelism which reproduces itself in the large and in the small fractures—in the fault as in the joint.[3]

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[1] See WILLIS, *loc cit.;* MARGÉRIE ET HEIM, *op. cit.;* VAN HISE, *loc. cit.*

[2] PHILLIPS, *Illustrations of Yorkshire*, Vol. II, 1836.

[3] DAUBRÉE, *Géologie Experimentale* (Paris, 1879), pp. 304–6.

A joint becomes a normal fault so soon as displacement occurs along its walls, and the essential difference, therefore, between normal faults and joints may be said to lie in this condition. An area of the earth's crust which has been deformed by jointing under compressive stress is thereby made especially liable to vertical changes of level, because its rigidity, and therefore its competency to uphold its load, has been reduced. Depression of the area, as a whole (and perhaps elevation of certain portions of it), will take place along the joint planes already formed. There is thus, probably, in all cases at least an infinitesimal displacement along the joint walls, and thus no sharp line can be drawn separating joints from faults.

Brögger, in his work upon the Langesund-Skien region of southern Norway, says of the joint and fault system:[1]

> "The dislocations, that is to say, the faults, have in fact cut the landscape through and through, and not alone parallel to one system of lines, but first chiefly parallel to two principal systems, and then also parallel to other less prevalent directions. . . . .
>
> If we consider how thickly the rocks are penetrated by very small faults, it follows, in fact, that a portion of the crust cut up in this fashion is built up like separate rectangular blocks of masonry.

The study in much detail of the circumscribed area of the Pomperaug valley in Connecticut and its vicinity[2] brought out facts quite independent of, but altogether harmonious with those discovered by Brögger in Norway.

In the Connecticut region it was shown that a system of nearly vertical faults falls into a number of intersecting series of parallel dislocations, of which four are quite prevalent, and that the directions of the series bear relations to one another, for which an explanation may be found in the mechanics of jointing under compression. A relation was also disclosed between the directions of the faults and the sizes of the included orographic blocks. It was further observed that the system of faults is parallel to and grades into the system of joints, and like it is spaced with an approach to uniformity. As regards the larger displacements of the area, it was found that they seldom occur wholly along one plane, but are distributed over a zone of parallel and near-lying planes — the throw is distributed.

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[1] W. C. Brögger, "Spaltenverwerfungen in der Gegend Langesund-Skien," *Nyt Magasin for Naturvidenskaberne*, Vol. XXVIII (1884), p. 401.

[2] Hobbs, "The Newark System of the Pomperaug Valley, Connecticut." *Twenty-first Annual Report U. S. Geol. Survey*, Part III (1901), pp. 1–160.

The faults of the less common series run along the diagonals of the larger composite blocks, and are believed to owe their formation to the downthrow of these blocks, and not to the original relief of the area from compression.

CRITERIA FOR RECOGNIZING A SYSTEM OF FOLDS.

While not necessarily present in all areas of disturbed rocks, it is fair to assume that in all areas of the crystalline schists in which bedded rocks are found, folds will be recognizable. The possibility of unraveling their relations to one another within a system will depend upon the intricacy of the structure, the frequency of the exposures, the freshness of the rock, the perfection of a combined joint and fault system, etc.

In general it may be said that flow structures and those produced by fracture are in contrast, the former exhibiting warped (curving) surfaces, and the latter plane surfaces. The courses of the fold structures across the map are, therefore, curved lines, whereas the latter course over the map in straight lines, or in zigzags made up of rectilinear elements. The courses of fault structures upon the map are little disturbed by the relief of the topography in proportion to their inclination — hade, being absolutely unaffected by topography when the hade is 90°. The nature of known formation boundaries upon the map, and that of other structures is thus one of the most important considerations in the determination of the kind of deformation to which the area has been subjected. When alternations of pitch of folds are not present, folded rocks present also rectilinear boundaries, but this consideration loses importance in most areas of intricate geological structure, because evidences of pitch can generally be made out. Change of pitch has been described as characteristic of few areas, because, as already explained, it has until comparatively recently seldom been looked for.

Other indications of the presence of flexures within a given area are observed at the individual exposures. In areas of folded rocks minor curvings of bedding planes are usually exhibited, and generally in great perfection. Changes in the strike and the dip of the beds are, when large or numerous exposures are found, observed to be, in general, gradual rather than abrupt; and, if abrupt, search will reveal intermediate values for the dip, or the strike, or both, as the case may be. Foliation planes are characteristic of, and connected with, folding, but not with faulting.

CRITERIA FOR RECOGNIZING A SYSTEM OF FAULTS.

The characteristics of a jointed and normally faulted area of the earth's crust have been touched upon in the last section. With abundant outcrops this structure may be disclosed upon the areal map by the generally rectilinear or zigzag boundaries of formations. If not, some indication may be afforded by the prevalence of straight lines and sharp bends in the topography, particularly if the lines fall into parallel and intersecting series. Such a relief may not be apparent without careful examination of the map, for the reason that the particular combination of directions is not known, and it may yet be quite striking when once discovered. Again, the drainage lines may compose a network which in direction conforms both to that of the topographic lines, and that of the formation boundaries. The prominent joints observed at the individual exposures, it may be supposed, will also be in conformity with the directions of the geologic and topographic lines above enumerated. This has never been better expressed than in the classic work of Professor Th. Kjerulf upon the geology of southern and central Norway, which concludes with these words:

> Thus the great systems of fissures which cut up the surface produce the primary lines in the aspect of the surface of Norway. The mysterious network of these lines is stamped in indelible characters; this may indeed remain a long time unnoticed; if, however, it has once been seen, it will never again escape observation. Like a moss-grown inscription upon a plate of marble, it is there and may be recognized. Here all embodied representations of plateaus, of tilted plains, and of every sort of erosion have not prevailed to hide the writing or to withdraw it from observation. Push these all aside and

the eye again sees the runic characters, and it depends only upon this, that they all be correctly understood in the future.[1]

The observation of these striking lineaments of the surface, however, unless they be of great perfection, hardly furnishes an adequate demonstration that an important deformation by faulting has occurred. The proof of this must rest upon the discovery of a considerable number of individual faults whose directions relegate them to a system of parallel and intersecting series. The methods by which individual faults may be recognized will be outlined in the sequel.

KEY AREAS FOR DETERMINING THE MANNER OF DEFORMATION OF A REGION.

In geological mapping it is almost an unwritten law that geological sequences must be established at points where formations appear in their larger masses at the surface, it being assumed that structural relations are in such cases the simpler. Areas which show a considerable number of formations brought closely together in small masses at the surface are looked upon with suspicion as areas of local and "minor" faulting, or as containing intercalated beds of unusual types due to purely local conditions of sedimentation. Whichever of these views is assumed, the areas are likely to receive but small attention; first, because the problem of their structure is difficult to unravel and not regarded as affecting the larger questions of the region; and, second, because if once unraveled, the scale of the map would not allow of its representation. Such areas are, therefore, most frequently represented upon the map in the color of the formation which is believed to compose their greater part.

However unsuited these intricate areas may be supposed to be for establishing the order of succession of geological formations, they are nevertheless, it is believed, in many cases the keys (and perhaps the only ones) to unlock the secret of the manner of deformation which has affected the area as a whole. Complicated indeed, they often require only patience and industry for their unraveling, whereas the larger masses by their very simplicity of areal distribution allow of several hypotheses, any one of which would adequately explain them.

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[1] *Op. cit.*, p. 334.

NATURE OF EVIDENCE FOR ESTABLISHING A FAULT.

The several ways in which individual faults may be discovered the writer has elsewhere recited.[1] Some of them are alone sufficient as proof, while others must be regarded as offering incomplete evidence to be weighed in connection with additional observations. As modified for the problem before us these methods will now be considered. Many of them could apply equally to thrusting or to normal faulting, but observation of fault hade will generally be sufficient to determine which in a given case is present.

1. *The observation of beds formed at different times in juxtaposition along a plane transverse to their bedding.*—With conformable formations such an observation may be regarded as absolute proof of a fault, and is, in fact, one concerning which there is no disagreement among geologists. It is only rarely, however, that such a contact will be found exposed, and hence the method serves but seldom.

2. *Offsetting of formations in outcrop.*—Almost equally reliable as a method for determining a fault is the offsetting of formations in outcrop. If in following the mutual boundaries of two formations, the formations are found abruptly thrown to the right or left and continued either along the old or in a new direction, it is only necessary to show that the core of a pitching fold has not conditioned the break of continuity to prove the presence of a cross fault. When several such faults occur in series with throw in the same sense, either the apparent course of the boundary as a whole is given a different rectilinear direction, or a crescentic outline is conditioned. The crescentic ridges which are so prominent a feature of the Connecticut valley are produced in this way. The three ways in which such ridges may be produced by normal faulting have been elsewhere pointed out.[2]

3. *Offsetting of outcrops as definite topographic features.*—With rocks which are resistant to the erosive agencies, or where fault-

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[1] *Twenty-first Annual Report, U. S. Geol. Survey*, Part III, pp. 85–93.

[2] HOBBS, *loc. cit.*, pp. 95–8.

ing has been accomplished in a not too early geological time, orographic blocks may cause a distinct offsetting of elevations upon the general surface and display an arrangement in zigzags or *en échelon*, which it is difficult to explain upon any other basis than that of normal faulting. Fig. 1 shows by the outline of the wooded area the serrated border of schist outcrops due to this cause. In Fig. 2 are exhibited four distinct orographic blocks of limestone arranged *en échelon* and owing their position above the general level to a skeleton work of silica which has fitted them to withstand the gnawing effect of erosion.

4. *Dikes.*—It has long been recognized that dikes of igneous or aqueo-igneous rock, and veins whose walls are plane surfaces, represent the positions of either joint or fault fissures which have been subsequently filled. Especially in the Harz mountains of northern Germany has this method of finding the position of old planes of dislocation been successfully employed.

5. *Abrupt changes of strike and dip not indicated in folds.*—An essential characteristic of every folded area is that gradational values can be found to correspond to all important changes of strike or dip, owing to the fact that folds appear in curves in nearly all of their sections (with undulating crests and trough lines in all sections, otherwise in all sections except those parallel to crest and trough lines). With excessively sharp pitching folds, changes of strike and dip by small amounts may be as abrupt as though caused by faults, but search will generally reveal at the apex, in the one case the core of the fold, and in the other the evidences of rupture, although it is quite possible that both will be found together.

6. *Discovery of fault breccia.*—*Reibungs* or fault breccia is very generally found where fault planes of considerable throw are actually uncovered. It is also often found in other places and especially in pits and shafts where access to the wall rock is not possible. Even in these cases, however, it furnishes valuable evidence that faulting has occurred. The formations which are in contact along the fault plane are likely to be indicated by the angular fragments of the breccia, which are usually cemented together by calcareous or siliceous material.

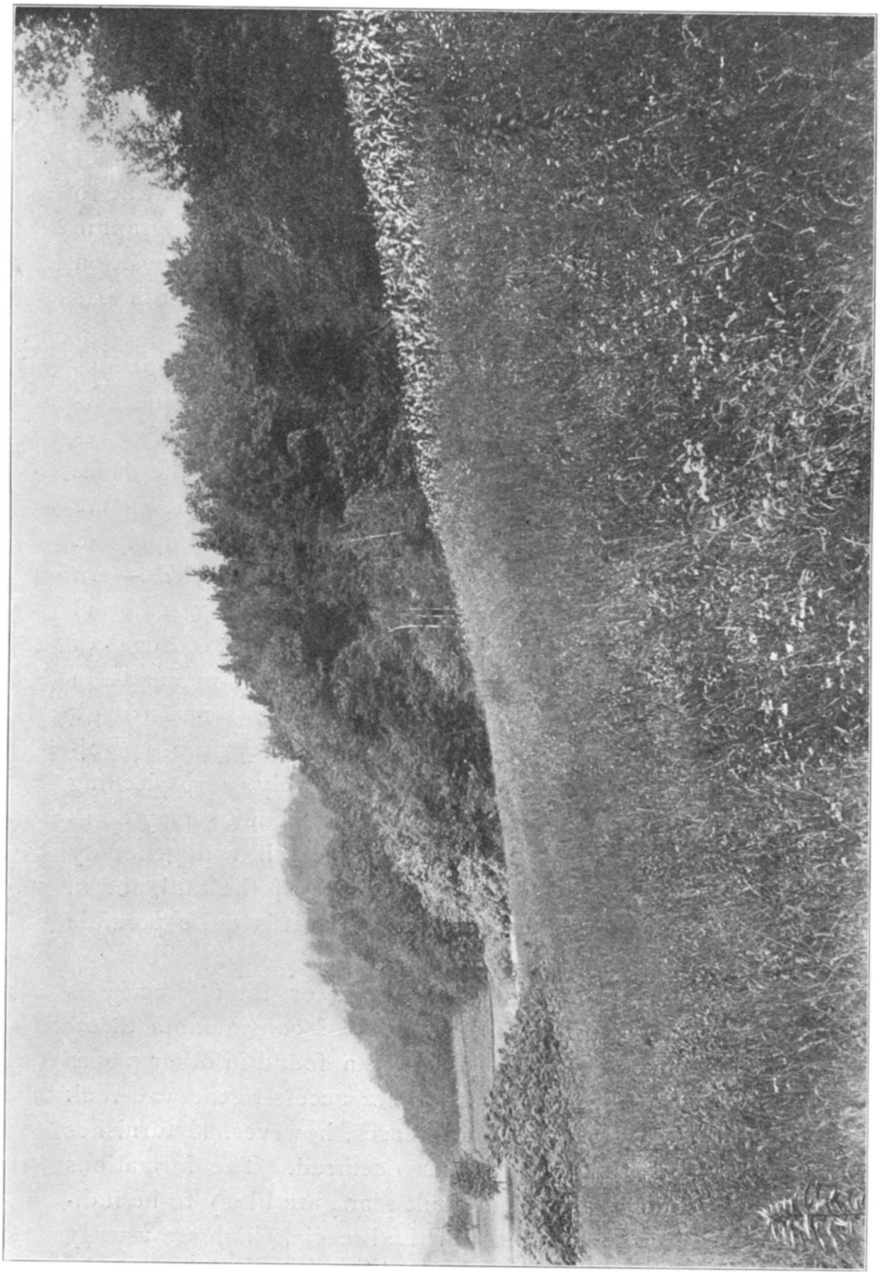

FIG. 1.—Normal faults indicated by offsets of areas of outcrop in the topographic features. View looking north-northwest along the western flank of the Laurel Lake Ridge, Lee, Mass.

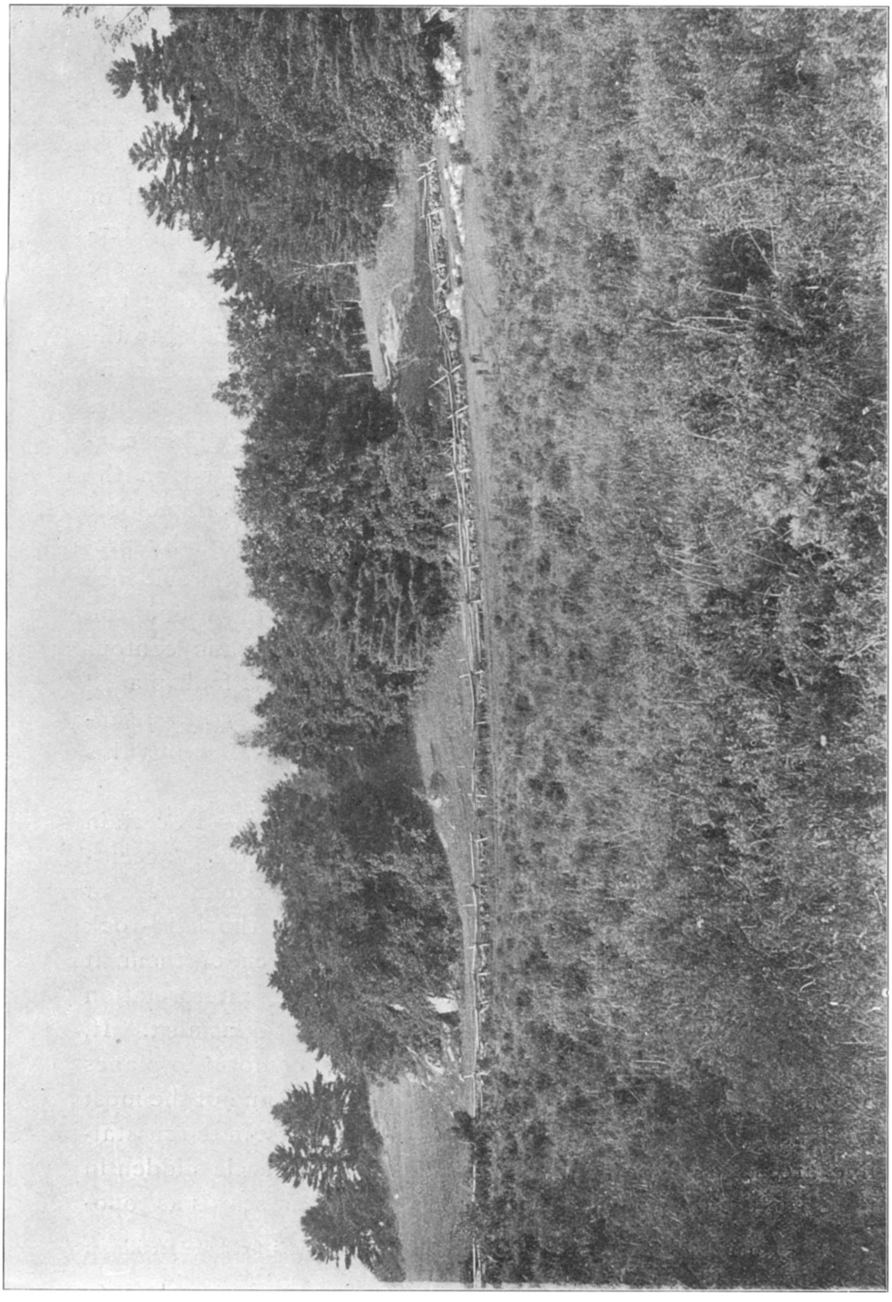

FIG. 2.—Small orographic blocks of silicified limestone arranged *en échelon.* View looking east at a point one and a half miles northwest of Ashley Falls, Mass.

7. *Observation of slickensides.*—While offering contributary evidence in many instances, observation of slickensides is one of the less important methods of locating a fault, and it could hardly be used without other evidence.

8. *Disappearance of outcrops along a rectilinear boundary.*—As already pointed out, little notice seems to have been taken of the way in which outcrops and areas of near-lying outcrops terminate, though in the opinion of the writer such boundaries are full of meaning. When outcrops or groups of outcrops terminate in right lines which are at the same time parallel to the strike of the beds and to the topographic contour lines, no special explanation is required. If they terminate in right lines across the strike of the beds, but along the topographic contour lines, their explanation may be found, either, first, in the erosion history of the region with no dependence upon geologic structure planes; second, in the valley lines as fixed by preexisting fault planes; or, third, in a fault scarp still in evidence at the locality. If the outcrop boundary is a right line and neither parallel to strike of beds nor to topographic contour lines, it is pretty sure to represent the position of a fault plane.[1] In glaciated areas regard must, however, always be had to essentially local and irregular accumulations of drift as affecting this explanation.

9. *Occurrence of scarps in the more resistant rock.*— In certain areas, at least, of the crystalline schists in which there is accentuated topographic relief, scarps are among the commonest of the physiographic features. In the mapping of the hard-rock geology account has, however, rarely been taken of them, it being perhaps rather generally assumed that their interpretation is the special field of the physiographer and glacialist. If, however, it can be shown that their directions conform to planes of jointing and faulting, their study will furnish some of the most fascinating and instructive lessons for the geologist in the crystalline areas. It is doubtless because their secrets lie hidden in the structure of the underlying rocks that rock scarps as topo-

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[1] See HOBBS, *loc. cit.*, pp. 89–91 for special cases of faults fixed by rectilinear boundaries of outcrop.

graphic features have received so little consideration at the hands of the modern school of physiographers.

The perfection of rock scarps will doubtless be dependent primarily upon the resistance of the rock of which they are formed to the agencies of erosion, and to the time that has elapsed since their formation. In dense basalt their life is probably the longest, and the present surfaces will most nearly represent the original fracture planes. It is a fact of general observation that scarps are usually interrupted in such a way as to produce a step-like structure, which suggests in nearly all cases that the throw was distributed over several parallel and near-lying planes. The great cliffs of the Newark basalt of the Connecticut valley produced in an unknown period of post-Newark time, furnish striking illustrations of rock scarps in great numbers and perfection.

The evidence that precipitous rock walls are connected genetically with the fault and joint system of a region — an inherently probable supposition — must be drawn from a study of the direction, not of a single cliff, but of a large number of scarps embracing a considerable area. Accurate topographic maps are most instructive in this regard, but they fail to tell the full story. Photography here comes to the aid of the geologist, not only in recording topographic peculiarities, but in the exposition of them. To give to photographs their full sphere of usefulness, however, it is important to indicate upon the map from what points they were taken and the pointing of the camera at each locality. A photograph common and uninteresting in itself becomes full of meaning in its relation to the map. A character like Fig. 3 entered upon the map and consisting of a circle which incloses the point at which the view was taken, and proceeding from the circle a short arrow to show the camera pointing, will supply the needful information. A figure within the circle refers to the number of the photograph or to the plate of a report, as the case may be.

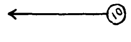

FIG. 3.

Scarps may, however, be produced in other ways than by faulting. Other agencies most potent to produce them are:

first, in glaciated regions the ice mantle which has carried away blocks from the lee side of elevations lying in its path; and, second, in regions of severe climate, the frost, which has separated blocks and allowed them to roll down steep slopes. A special cause of scarp formation may be the undermining by solution of beds of calcareous rock, which has allowed the overlying beds to fracture and fall. In all cases, however, some earlier structure planes must be assumed along which the block has separated, and these planes may have been either planes of jointing, or faulting, or foliation, or of original bedding. Considering each scarp by itself, therefore, and quite independent of the system of the region, it is more likely to represent a fault in proportion: first, as it does not face in the direction in which the ice mantle moved over the area; and, second, as it is not parallel to a plane of fissility or of bedding (not parallel to the strike).

Study of the southern New England area has shown that cliffs of considerable extent which adhere to a uniform trend often for long distances usually do so, not along a single plane, but by a series of minor zigzags the elements of which are joints or faults of other series combined with the one which corresponds in direction with the general trend of the cliff.[1] Fig. 4 will illustrate the manner in which it is accomplished. Such a composite cliff is shown in Fig. 5. Figs. 1 and 10 must be regarded as showing the same type of structure, but in the next higher orders of magnitude, respectively, within a composite series. This observation of the composite nature of lines of dislocation is regarded as of much significance in showing the genetic connection of faults and joints, as well as in reading the geological structure of an area.

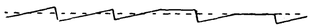

FIG. 4.

10. *Fault gorges.*—In many places, and especially throughout New England, are found deep clefts in the harder rock which are locally known as "purgatories," "devil's dens," "ice-glens," "ice-gorges," etc. The walls of these clefts are nearly or quite

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[1] *Vide* BRANNER, "Geology in its Relation to Topography," *Trans. Am. Soc. Civ. Engineers*, Vol. XXIX (1898), p. 63.

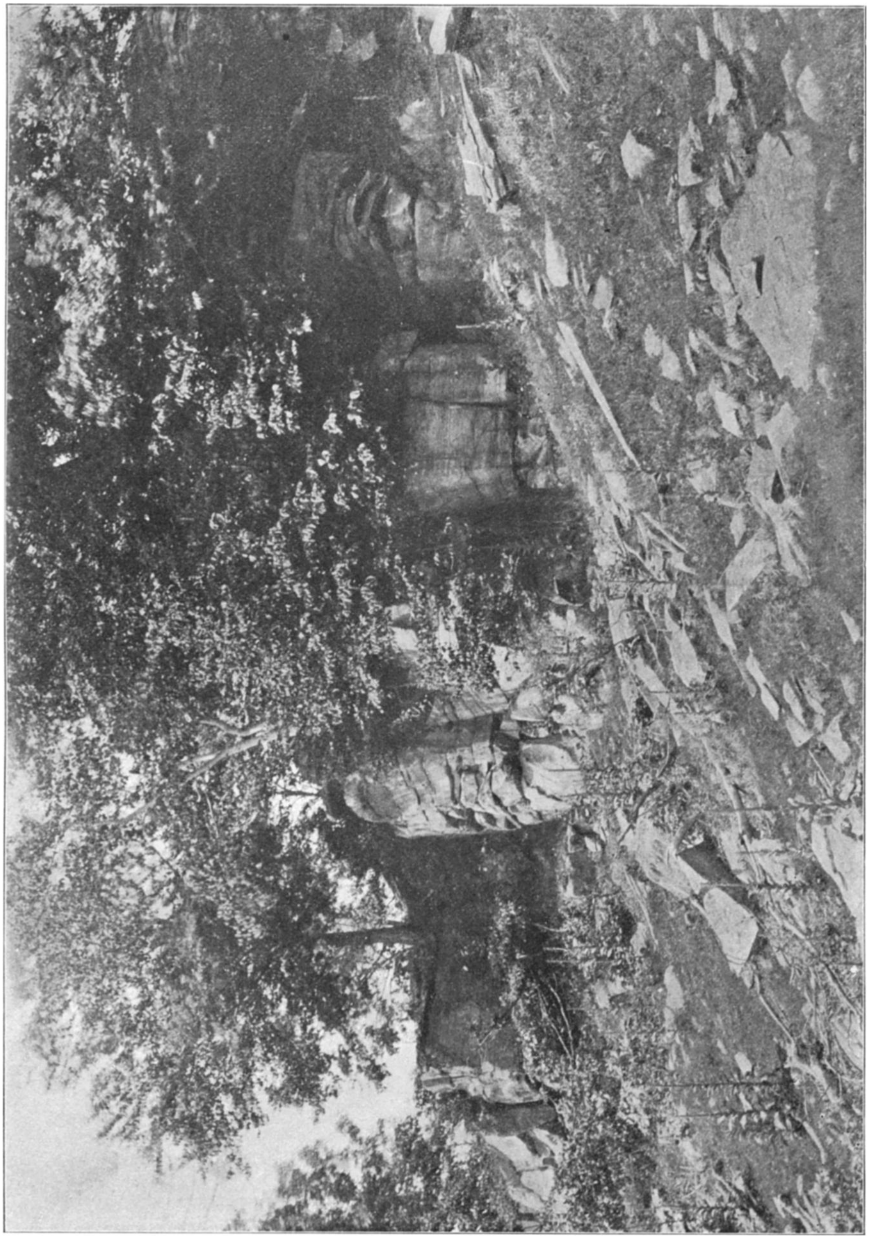

FIG. 5.—Cliff essentially rectilinear in direction produced by faulting and composed of many faults of a lower order of magnitude. Southeast wall of the Cobble, Tyringham, Mass. The wall trends N. ± 38° E. for nearly a mile, the smaller faults striking N. ± 38° E., N. ± 70° W., N. ± 10° W., etc.

perpendicular, and their bottoms are occupied, not by a stream, but by an accumulation of great angular blocks composed of the same material as the walls. Deep below this accumulation of blocks one may sometimes thread his way until the ice and snow of the preceding winter are found unmelted even at the end of summer. Such gorges find their simplest explanation in the local depression of a long and narrow orographic block along vertical joint walls (*Graben*), with the accompaniment of much fracturing and dislocation in the block itself. (See Figs. 6 and 7).

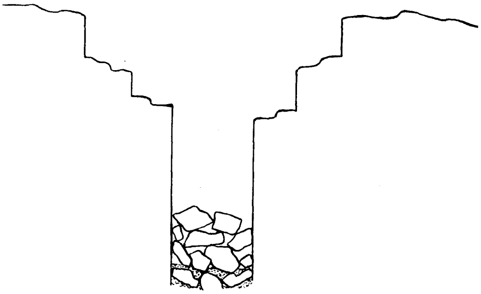

FIG. 6.—Cross-section of fault-gorge (so called "ice-gorge") near Hartsville, Mass. The stippled area represents snow and ice.

11. *Arrangement of surface springs in right lines.*—Since the time of Daubeny and Forbes the locations of springs have been connected with fissures. Peale in his report upon the mineral waters of the United States cites many regions where springs are arranged along fault planes, and, speaking of the Great Basin, says: "A map of the hot springs of the Great Basin would be, to a great extent, a map of its displacements."[1] Regions might be multiplied where essentially the same facts have been observed.

NATURE OF EVIDENCE FOR ESTABLISHING A SYSTEM OF FAULTS.

Observed faults are in parallel and intersecting series—Having made out within a region the presence of a number (larger or smaller) of normal faults, it is next to be determined whether they stand in any relation to one another If a considerable number have been observed, it is likely that some will be found to be parallel, or as nearly parallel as the errors of observation allow. Evidence of this nature is, however, valuable in propor-

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[1] PEALE, *Fourteenth Ann. Report U. S. Geol. Survey*, 1894, Part II, pp. 63, 64; see also RUSSELL, *Fourth Ann. Report U. S. Geol. Survey*, 1884, p. 452; HILL AND VAUGHAN, *Eighteenth Report, ibid.*, 1898, Part II, Plate XLVI; HOBBS, *Twenty-first Report, ibid.*, Part III, pp. 91-3.

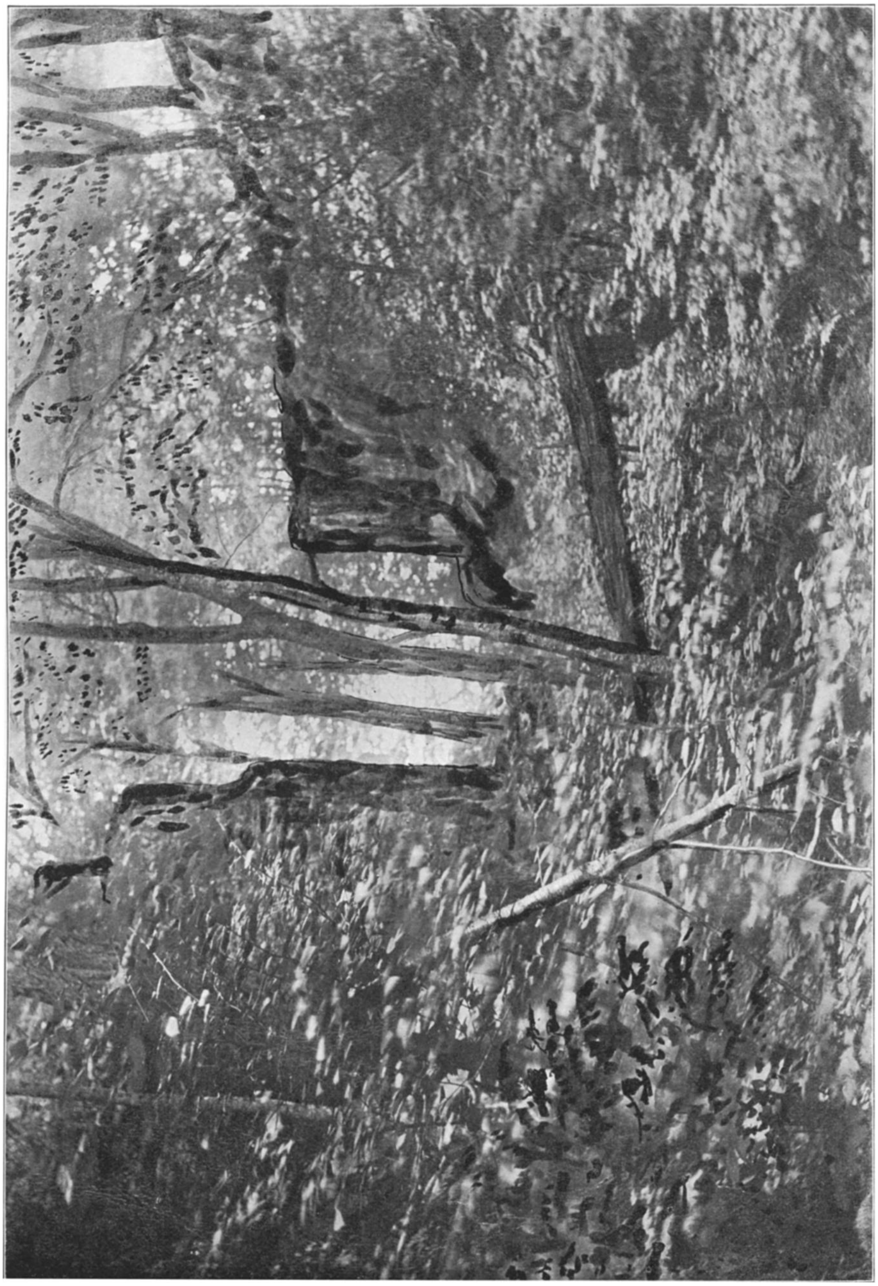

FIG. 7. —A gorge produced by faults. The "Ice Gorge" near Hartsville, Mass. The view is from within the gorge and looks toward the entrance.

tion as the number of observed faults is large. It has been observed in the Pomperaug valley and fully confirmed by experience gained subsequent to the publication of the report upon that area, that a regular spacing of normal faults is as characteristic of them as it is of joints. It is, therefore, often possible to determine not only the shape but the size of orographic blocks included between series of normal faults within a system or network.

2. *Observed faults are parallel to the joint system.*—In this observation lies the most important evidence that the region as a whole is affected by a system of normal faults genetically connected with its system of joints. Not only is it to be observed whether the two systems are parallel, but, if so, it is to be noted whether any simple relation connects the direction of the individual joint and fault series with the dimensions of the orographic blocks which they have conditioned.

3. *Zigzag topography.*—The study of the topographic map supplemented by observation and by photographs made in the field may show that the physiographic features are bounded by straight elements which coincide in direction with the network determined by the joints and faults. Figs. 9 and 10 represent topography of this type, the one from the intricately faulted Newark area near Meriden, Conn., the other from the crystalline belt of Berkshire county, Mass. A good illustration also of this type of topography is Monument Mountain in Berkshire county, whose main mass is composed essentially of a single fairly uniform formation and is believed to owe its exceptionally rugged topographic development almost solely to its joint and fault planes. (See Fig. 8.)

In the paper which has here been so frequently cited for illustrations of fault structures the writer has used the expression "floating block topography" in reference to a very striking physiographic development, by which are revealed orographic blocks, generally of similar size and shape standing at different altitudes and with bounding fault-planes in evidence as scarps. Fig. 11 displays such a type of physiographic relief. It is to be noted that the blocks of this type (for convenience "unit"

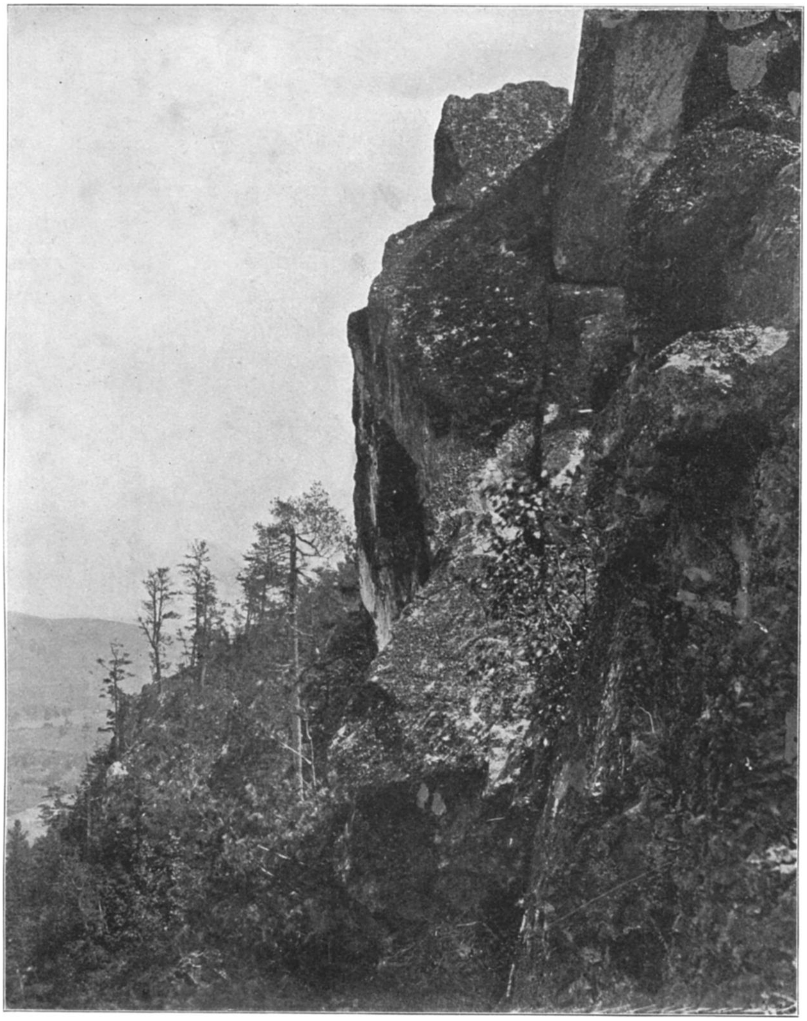

FIG. 8.—Details of topography of Monument Mountain, near Stockbridge, Mass.

blocks, though subdivided by faults and joints) are sometimes grouped into hills—composite blocks—which are spaced over the general surface much like the black squares of a checker board. Fig. 11 exhibits about two-thirds of such a hill in a series of the kind described. Fig. 2 is a detail taken from another hill of the series.

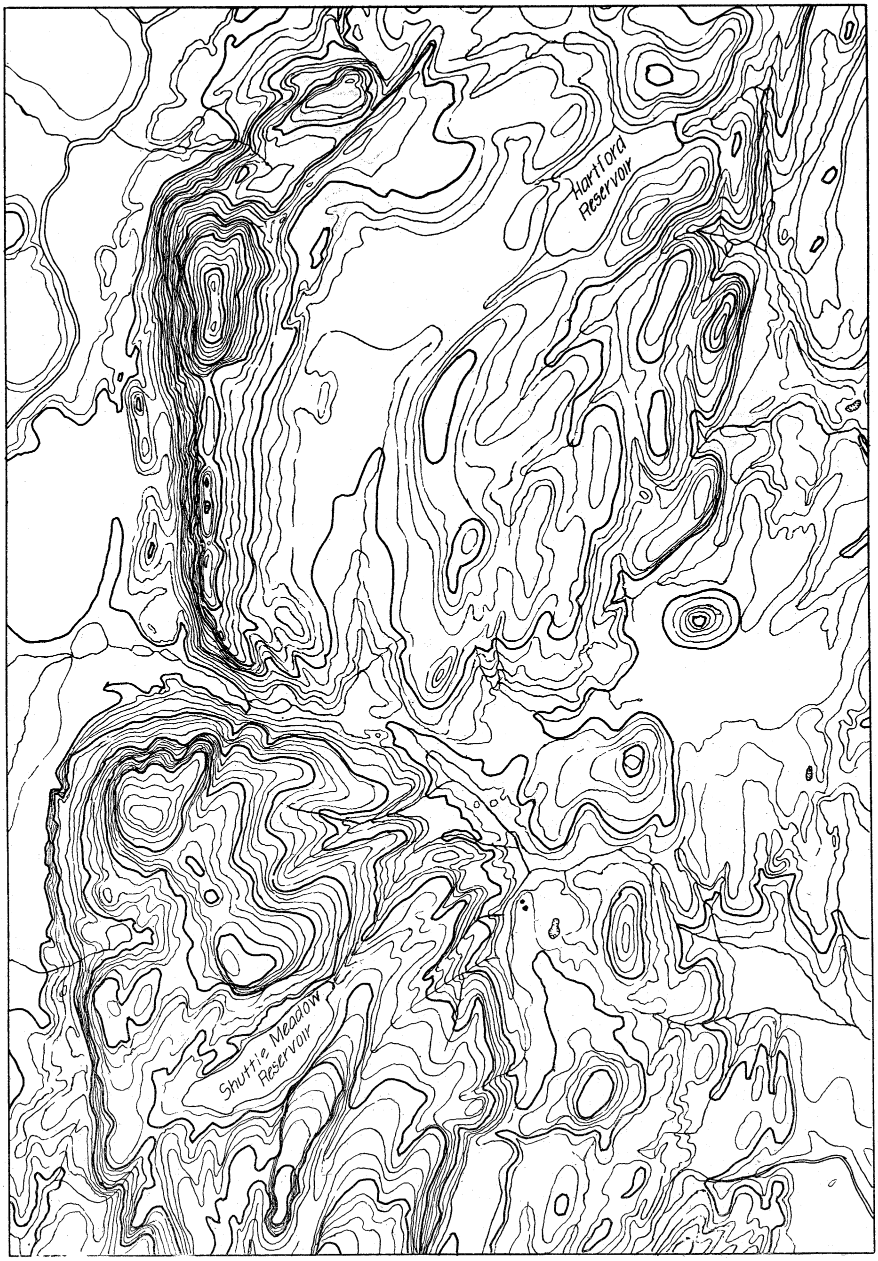

FIG. 9.—Zigzag topography of unfolded but normally faulted Newark rocks. Scale one inch equals one mile. From the Meriden sheet of the map of Connecticut by the U. S. Geological Survey.

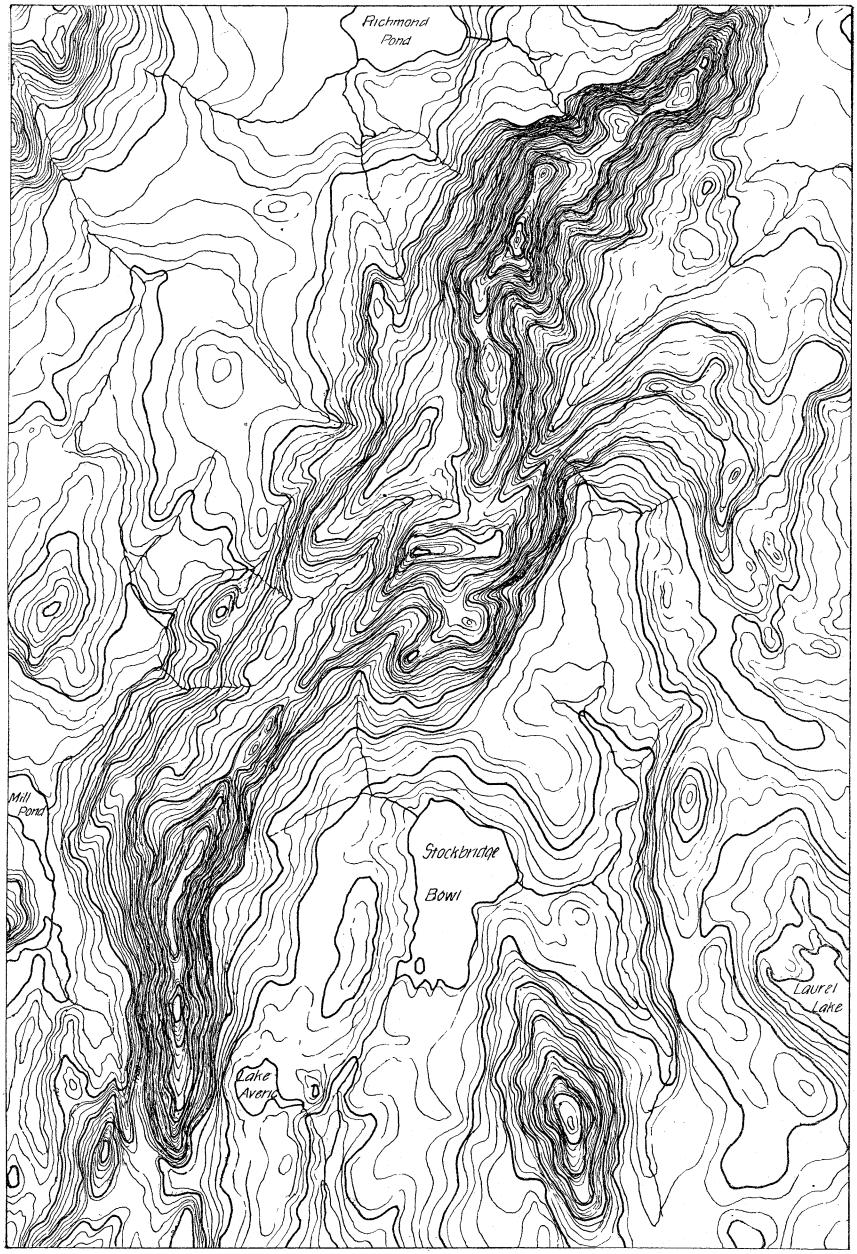

FIG. 10.—Zigzag topography in the crystalline schists. Scale one inch equals one mile. From the Pittsfield sheet of the map of Massachusetts by the U. S. Geological Survey.

4. *The drainage system a network of parallel and interesting series.*—The recognition of the fact that a system of joints and faults has been responsible for the present directions of streams within any region, aside from purely theoretical considerations of the closet naturalist, must be credited to Professor Theodor Kjerulf, the former director of the Geological Survey of Norway. His study of the newer and accurate topographic maps of the country led him to see in the courses of the valleys, lakes and fjords, the lines of dislocations.[1] The occurrence in many areas of similarly regular networks of streams in which the elements are essentially straight lines in parallel series over considerable distances has now long been known, and has been given an adequate explanation by Daubrée as conditioned by the system of fractures (*lithoclases*) of the region, in part by the faults (*paraclases*) and in part by the joints (*diaclases*).[2] Daubrée cites the works of many geologists to show that such stream networks have been observed in many widely separated areas. Since the appearance of his work (1879), numerous other examples have been added.[3] Löwl, in his work on valleys,[4] treats the subject under three heads—fold valleys, fault valleys, and erosion valleys. He mentions the Rhine and the Leine in Germany and the Piave in the southern Alps, as well as other valleys, which are of the fault type.

Daubrée appears to ascribe the orientation of the larger number of stream channels to joints rather than faults, his view

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[1] KJERULF, *Geologie des südlichen und mittleren Norwegens*, auth. German ed. by AD. GURLT (Bonn, 1880), pp. 328–34. See, however, in this connection, STUR, "Das Isonzothal," etc., *Jahrb. d. k. k. geol. Reichsanst.*, Vol. IX (1858), pp. 324–66, and plate.

[2] DAUBRÉE, *Géologie experimentale* (1879), pp. 332–73.

[3] SUESS, *Antlitz der Erde*, Vol. I (1885), p. 339. BRÖGGER, "Spaltenverwerfungen in der Gegend Langesund-Skien," *Nyt Magasin for Naturvidensk.*, Vol. XXVIII (1884), pp. 253–419. "Ueber die Bildungsgeschichte des Kristianiafjords," *ibid.*, Vol. XXX (1886), pp. 99–231. KEMP, "Preliminary Report on the Geology of Essex County," *Report of State Geologist of New York for Year 1893*, Albany, 1894, pp. 438–40. VAN HISE, "Origin of the Dells of the Wisconsin." *Trans. Wis. Acad. Sci.*, Vol. X (1895), 556–60. HOBBS, *loc. cit.* chap. v., also "The River System of Connecticut," JOUR. GEOL., Vol. IX (1901, pp. 469–85).

[4] LÖWL, *Thalbildung* (Prag, 1884), pp. 19–43.

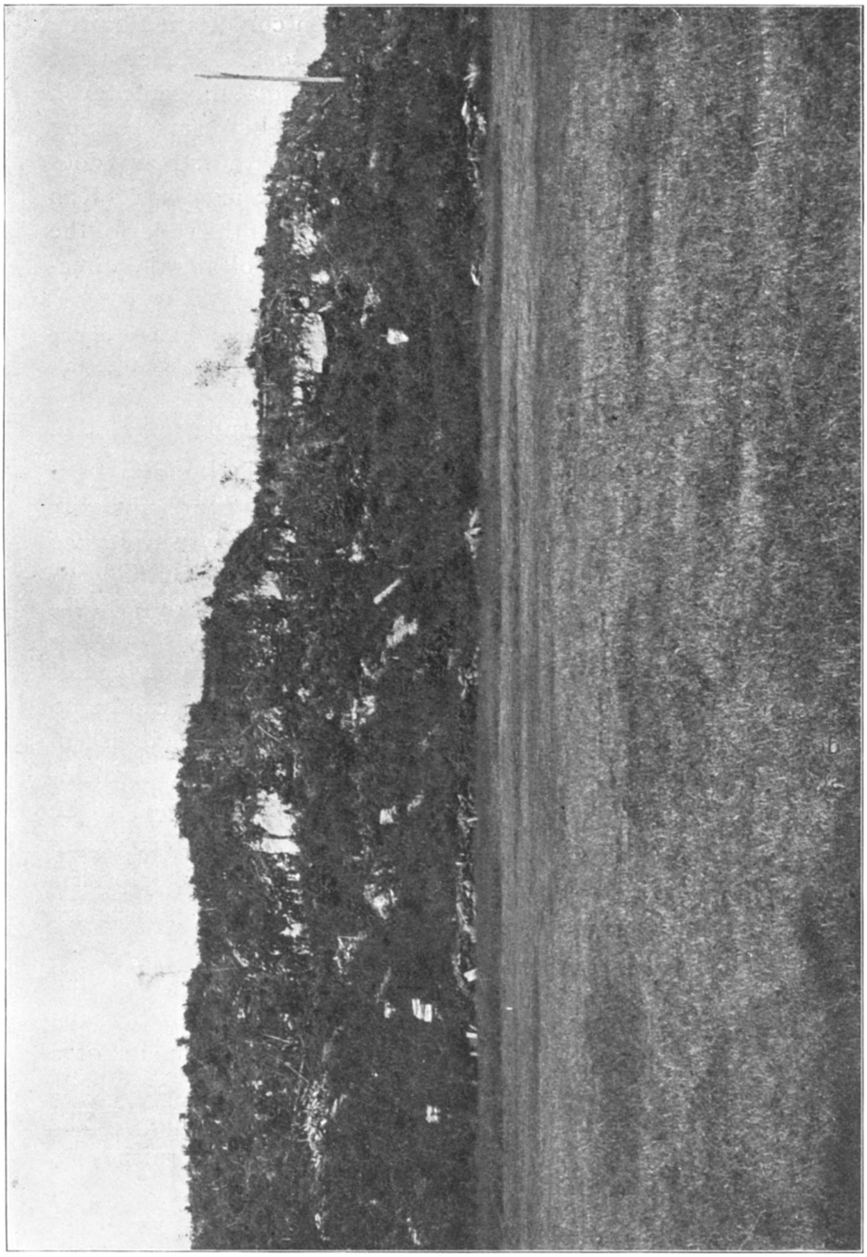

FIG. 11.—"Floating block" topography. Northwest of Ashley Falls, Mass.

being that the course of the stream has been conditioned by the gaping of the joint fissure, and he finds in some instances that the beds on opposite sides of the stream stand at the same level. Löwl takes account of the lateral translation of streams working in inclined strata, and argues that the bed of the stream does not represent the position of the fault, which in many cases can be observed high up upon the slope. Speaking of the valley of the Oder in the Harz mountains, a stream which follows the direction of the Oder fault, he says :

> The Oder valley is therefore nothing more than a performance of the flowing water. Its course along a line of disturbance proves only that this directed the erosion into a definite course.

The writer, by taking account of the great number of parallel faults within a series, would ascribe the courses of the streams within a network more largely to the presence of many long and narrow down-thrown orographic blocks (*Graben*), which have conducted the water like canals.[1] Upon this assumption the equal altitude of the strata upon opposite sides of a valley does not preclude the probability of faults along the bed of the channel. Whatever explanation be offered of the directing of streams upon a large scale by joints and faults, there can be no doubt that streams are of greatest service to the geologist in showing the *directions* rather than the *positions* of lines of dislocation. Regular networks of streams may be assumed to be much more common than the literature of the subject would indicate, for the reason that comparatively little attempt has been made to explain stream directions on the basis of structure planes of the underlying rocks.

5. *Zigzag course of coast lines.*—Evidence of the same kind as that derived from drainage systems is sometimes to be supplied by coast lines, which may disclose the lineaments of a submerged drainage system, the border of a sunken composite orographic block, or a margin of areas of outcroppings. The coast of Scotland between Sutherland and Ross furnishes an illustration.[2]

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[1] *Twenty-first Ann. Report U. S. Geol. Survey*, Part III, p. 149, Pl. XVI., JOUR. GEOL., Vol. IX, p. 483.

[2] JUDD, "The Secondary Strata of Scotland," *Quart. Jour. Geol. Soc.* (1873), pp. 131, 134, Pl. VII ; see also SUESS, *op. cit.*, Vol. I, p. 269.

It should be by a consideration of all the above outlined methods that the presence or absence of a fault system should be determined for any given area.

METHOD OF MAPPING A CRYSTALLINE AREA DEFORMED BY A SYSTEM OF FOLDS IN CONJUNCTION WITH A SYSTEM OF FAULTS.

The discovery that the beds within a region of crystalline schists have assumed their present attitudes in consequence of deformation of the area by a system of folds in conjunction with one of normal faults, greatly increases, it must be admitted, the difficulties in the way of accurately setting forth the geology upon maps. The question may well be asked whether even with patience and industry the areal distribution of formations can be adequately represented. Where outcrops are abundant and well distributed, and where formations are sharply differentiated petrographically, the difficulties can be overcome; but where gneiss, schist, and quartzite types by reason of gradational members are with difficulty distinguished, even under favorable conditions, their appearance in a fault mosaic will in many cases defy the most skillful worker to unravel.

To fix the order of succession of formations, it will be necessary, not only to exclude the possibilty of an overturn (as by finding the arch of a cross fold), but actually to follow one formation beneath the other.

In other ways the problem of mapping will be simplified. The appearance of formations, first in one areal succession, and again in a different succession not to be accounted for by overturning, will find an adequate explanation. Upon the theory that folding alone has accomplished the deformation of an area of crystalline rocks, geological sections have been strained literally and figuratively beyond the point of rupture. The mechanics of folding is now pretty well understood, and the appearance in geological sections of synclines which have one limb several times the thickness of the other (a not uncommon means of adjusting to theory) finds, it is believed, as little warrant in mechanics as it does in observation.

In explaining an intricately faulted area on the basis of deformation by folding only, it is also the tendency to make geological formations much more heterogeneous than they really are, until at last they have so many different phases that all distinguishing petrographic differences are lost. With the broader interpretation petrography will take a higher place in geological mapping.

It is the intention of the writer in another place to present with the aid of maps and photographs some concrete examples of areas within the belt of crystalline schists where deformation has been accomplished in part by folding and in part by a system of faults.

WILLIAM HERBERT HOBBS.

MADISON, WIS.
September 1, 1902.